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Proposal Title

Measurement of the $\Delta\Delta$ component of the Deuteron by Exclusive Quasi-elastic Electron Scattering

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Proposal to the C.E.B.A.F. Program Advisory Committee

Measurement of the ΔΔ Component of the Deuteron by Exclusive Quasi-elastic Electron Scattering

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Abstract

We propose to use the CLAS spectrometer to search for direct evidence of the predicted $\Delta^{++}\Delta^{-}$ component of the deuteron by quasi-elastic electron scattering from the Δ^{-} with detection of the scattered electron and the decay products of the spectator Δ^{++}. The large acceptance of the CLAS will allow kinematically complete event measurement with high statistics, so tight background rejection cuts can be used. This should permit greater sensitivity than any previous measurement, down to or below the level of most predictions. If a signal is seen, it should be possible to map out the momentum distribution of the spectator Δ's, and to study the response function of the struck Δ over the range $0.1\ (\mathrm{GeV/c})^2 < q^2 < 1.\ (\mathrm{GeV/c})^2$.

A total of 25 days (600 hours) of beam time is requested.

1) Introduction

It has long been believed that excited baryons must make a contribution to the ground-state wave function of nuclei. In fact, virtual excitation of the Δ is believed to dominate the three-body interaction. (Throughout this proposal, Δ will refer specifically to the $\Delta(1232)$ resonance, unless otherwise indicated.) No direct observation of these components has yet been made, however. This is largely because of the difficulty of cleanly distinguishing interactions on pre-existing baryons from the excitation of resonances by the probe's interaction with the target.

The deuteron is unique in that isospin conservation forbids the contribution of a single Δ excitation. The lightest Δ excitation which may appear in the deuteron wave function is the $\Delta\Delta$ (two-Delta) state. This offers the potential for a clean experimental signature based on the observation of a non-interacting spectator Δ resulting from a high momentum transfer interaction of the probe with the other Δ.

Many experiments have attempted to probe this component of the deuteron wave function indirectly by observing its predicted effects on electro-disintegration, elastic scattering cross-section, tensor polarization, quasi-elastic scattering, etc. As will be discussed below, a few experiments have sought direct evidence of such a component by observation of a spectator Δ after breakup of the deuteron. Several previous measurements have approached the level of sensitivity required to observe the predicted level of $\Delta\Delta$ component. However, those experiments were plagued by low statistics and/or loose, inclusive event definitions. We propose to seek direct evidence of the $\Delta\Delta$ component of the deuteron wave function by exclusive quasi-elastic scattering of electrons from one of the Δ's in coincidence with detection of the spectator Δ. The large acceptance of the CLAS spectrometer will permit the acquisition of a large set of kinematically complete events of this nature. These large statistics will permit us to impose tight cuts to eliminate many of those sources of background which were the limiting factor for the sensitivity of previous experiments.

The simplicity of the system also makes calculations for the deuteron more tractable than for other nuclei and a number of authors[1,2,3,4] have made calculations of the contribution of the $\Delta\Delta$ component to the ground state. Jena and Kisslinger[1] calculated the NN–$\Delta\Delta$ interaction in the one pion exchange approximation. Their coupled-channels calculation predicts a contribution of $\Delta\Delta$ to the deuteron wave function of $P_{\Delta\Delta} = 0.25\%$. ($P_{\Delta\Delta}$ is the sum of the squares of the amplitudes of the different $\Delta\Delta$ spin/angular momentum components, or the total probability of finding the deuteron in the $\Delta\Delta$ configuration.) Because of the large D-state component, the Δ momentum distribution is found to have significant strength at high-momentum, as shown in Figure 1.

Arenhövel[2] included ρ-exchange along with π-exchange in calculating transition potentials for an impulse-approximation calculation. He finds that the inclusion of ρ-exchange renders the calculation more stable with respect to choice of cut-off parameter. His calculation predicts the component of $\Delta\Delta$ in the deuteron as $P_{\Delta\Delta} = 0.7$ to 1.2% . A subsequent coupled-channels calculation by the same author[3] included ρ-exchange in the transition potential and both ρ– and ω-exchange in addition to π in the $\Delta\Delta$ coupling. Depending on details of the model the prediction for $P_{\Delta\Delta}$ was found to vary between 0.3% and 1%. Again, the ^7D state was found to play an important part.

A more recent coupled-channel calculation[4] has been made in which the diagonal channel potentials include the exchange of the π, ρ, ω, a_0, and η (along with the σ to model higher order exchange). The transition potentials are calculated from exchange of π, ρ, and a_0. Coupling constants for meson-Δ vertices are taken from the corresponding meson-nucleon couplings, within the framework of the quark model. This calculation predicts $P_{\Delta\Delta}$ of approximately 0.4% for the several different models considered. This calculation also predicts a significant contribution from the ^7D part of the $\Delta\Delta$ wave function.

It will be noted that the variation among these models is only moderate, with $P_{\Delta\Delta}$ ranging from 0.25% to 1.2%. Although the $\Delta\Delta$ component of the deuteron has not yet been observed experimentally, there is substantial agreement not only on its existence, but on the magnitude of its contribution to the wave function. Any large variation from the expected range must indicate a significant problem in our understanding of meson-baryon couplings within the quark model. It is also interesting to note that the inclusion of $\Delta\Delta$ components in the deuteron wave function plays a significant role in fitting inelastic electron-scattering data[5] and in explaining[6] the observed position of the minimum in the elastic-scattering form-factor, B(q).

2) Physics Motivation

Clearly there is great Physics interest in a direct experimental verification of the existence of non-nucleonic components in the ground state wave function of a nucleus. On the one hand, it may be viewed as inevitable that any channel which couples strongly to the nucleonic states must make a contribution to the eigenstates of the strong Hamiltonian. On the other hand, no experiment has yet directly confirmed the existence of any such exotic components. If sensitive experiments do not verify the expected contributions of components such as $\Delta\Delta$, they will call into question the legitimacy of baryonic states as the basis for expansion of hadronic configurations in nuclei. At the very least, the failure of such states to appear at the expected level would imply a surprising error in the present understanding of couplings of mesons to excited baryons and the resulting predictions for baryon-baryon interactions.

One of the unique advantages offered by the deuteron is the ability to tag interactions which occur on a pre-existing Δ. Because isospin conservation ensures that Δ's only appear in pairs, the observation of a Δ spectator may be used to isolate those events for which the target was a Δ. Thus it may be possible to directly map out the elastic form-factors of the Δ by examining the q-dependence of scattering to the $\Delta\Delta$ final state. Since the pre-existing Δ's in the deuteron are strongly interacting with each other at short range, it is possible that the form-factor so measured would not be the free-Δ form-factor. However, it is well know that the strongly interacting nucleons in nuclei can often be well approximated as retaining many of the properties of the free nucleon at moderate momentum transfer. The form-factors of bound Δ's would provide a new insight into short-range baryon interactions.

All attempts to directly experimentally verify the $\Delta\Delta$ component of the deuteron, including the present proposal, have hinged upon treating one of the pre-existing Δ's as a spectator. The spectator approximation is commonly invoked in the calculation of final state nucleon momenta due to Fermi motion or two-body correlations. The scale of energy which must be transferred to put the spectator Δ on shell is much greater here than in most such applications, however, if the three-momentum transfer to the struck Δ is large, then the sudden approximation may be invoked to argue that the spectator Δ is simply projected into the eigenstates of the new (free space) Hamiltonian, which suddenly applies. While this may add some complication in the interpretation of experimental results, it also provides an opportunity to study the mechanism by which such a particle, which would be far off-shell in the absence of the perturbing potential, reaches the mass-shell as the strong interaction potential is removed. As long as the struck Δ interacts as a single particle and is scattered away, the spectator must have isospin 3/2. We may expect the spectator particle to often retain its identity as a Δ even if its momentum distribution is somewhat distorted from that expected in the spectator model.

If the spectator approximation can be justified, at least for some subset of the kinematics, then the momentum distribution of the pre-existing Δ's in the deuteron can be determined directly from the measurements as it will be reflected directly in the momentum distribution of the observed spectator Δ's. Thus the validity of the spectator approximation can be tested in a high-statistics measurement by comparing the different spectator momenta distributions obtained for differing momentum transfer and/or spectator direction, which should be a universal function.

3) Previous Experiments

We will now briefly review some of previous experiments which have sought evidence of a pre-existing $\Delta\Delta$ component in the deuteron. It will be seen that the proposed experiment will be able to apply a much more restrictive set of selection criteria than any of the past measurements. The fact that several of the earlier works were able to set upper limits comparable to the expected signal level, despite their use of loose cuts, shows that background sources cannot be large and suggests that measurements could be successful if sensitivity was great enough to permit more selective cuts.

The earliest attempt to detect the $\Delta\Delta$ component of the deuteron was made by Benz and Söding[7] at DESY. This was an inclusive measurement of $\gamma d \rightarrow \Delta^{++} + X$ using untagged Bremsstrahlung photons of 1 to 5.5 GeV and making no selection of the final state, X. The only cuts which were made to eliminate background were a requirement that the Δ^{++} momentum be in the backward hemisphere and that the final proton momentum be high enough to exclude the possibility that it results from Fermi motion of a spectator proton. The latter cut was enforced only statistically, weighting events by the probability that they did not contain a spectator proton. The number of events they report (100) is consistent with $P_{\Delta\Delta} = 3\%$, if the total photon cross-section is taken as an average over the entire kinematic range. Subsequent measurements have shown $P_{\Delta\Delta}$

to be much smaller, as will be discussed below. We must conclude that the events seen in this experiment were mostly background, probably resulting from final state interactions which excited the spectator nucleon to a Δ^{++}.

In another experiment, a search of 1.3 million bubble chamber photos[8] for events containing a backward going Δ^{++} yielded event samples of only 20, 26, and 73 events, respectively, for beams of π^+ at 15 GeV/c, π^- at 15 GeV/c and K^+ at 12 GeV/c. The event sample was restricted to those in which the other particles were the scattered beam meson and a neutron-π^- pair. Because of the limited statistics, no cuts were put on $M_{n\pi}$ or, more significantly, on proton momentum. The 'decay angle' distribution for the p-π^+ shows that the data sample was badly contaminated by accidental pairing of a π^+ with a spectator proton. Despite this contamination the data set an upper limit of $P_{\Delta\Delta} < 0.7\%$ even if all such events were interpreted as signal. A similar data set[9], from scattering of 4 GeV/c π^+ on deuterium, set an upper limit on $P_{\Delta\Delta}$ of 0.8%. Again, there was no cut on proton momentum and the 'decay angle' distribution was highly skewed. The latter measurement may give some important insight into the level of background to be expected in this momentum range, which matches the present proposal. In the unbiased sub-sample of their events (i.e. that sample which had no upper limit on proton momentum) they searched for candidate Δ's at angles larger than 90° in the lab, with the Δ decaying backwards (to select against contamination from spectator protons), and with the other pπ pair also reconstructing to the Δ mass. They found only one such event, corresponding to a sensitivity of $P_{\Delta\Delta} = 1\%$. This provides a direct experimental upper limit on the contribution of final state excitation of the $\Delta\Delta$ final state in the momentum transfer range of interest.

Data from antiproton scattering on a deuterium bubble chamber[10] was searched for evidence of $\Delta\Delta$ events and a measurement of $P_{\Delta\Delta}$ as high as 16% was reported. The selection of events in which the proton stopped in the bubble chamber made the measurement very susceptible to accidental combination of pions with spectator protons. The reported Δ decay events were, in fact, found by a fit of a Breit-Wigner on top of a much larger phase space distribution. This clearly made the measurement very sensitive to model dependence in the Monte Carlo of background.

The most sensitive and most recently published measurement[11] used a high momentum neutrino beam on a deuterium bubble chamber. This is an inclusive $\nu\, d \rightarrow \Delta^{++} X$ measurement with no restriction on X (except that it contain an odd number of charged tracks). Furthermore, no cut was employed to eliminate spectator proton contributions. Despite this, their data is clean enough (probably because of the high momentum transfer) to set a limit of $P_{\Delta\Delta} = 0.4\%$.

A greater sensitivity has been claimed in an unpublished pre-print from the TAGX group[12]. Their method of estimating the $\gamma\,\Delta$ cross-section for low energy photons is highly suspect, however[13]. The quoted upper limit of 0.14% on $P_{\Delta\Delta}$ appears to be based upon a significantly overestimated sensitivity, resulting from the failure to properly account for the difference in phase space available with a two-Δ final state compared to two nucleons.

4) Proposed Measurement

We propose to observe the $\Delta^-\Delta^{++}$ component of the deuteron by scattering electrons quasi-elastically from the Δ^-, as represented in Figure 2. Observation of the decay of the spectator Δ^{++} and the scattered electron will allow selection of those events for which the unobserved hadrons have a missing mass in the Δ^- region. Of these d(e,e' p π^+) Δ^- events, a sub-sample will also include detection of the π^- from the Δ^- decay, allowing reconstruction of the neutron mass as a double check that the final state includes only Δ^{++} and Δ^-. If this subsample indicates significant contamination of the main data set by backgrounds, such as d(e,e' p π^+) n π^0 π^-, then the analysis may be limited to the more restrictive d(e,e' p π^+ π^-) n data set, with some loss in event statistics being traded for high selectivity of good events.

The goal for sensitivity of this experiment will be the ability to detect the $\Delta\Delta$ component even if its contribution to the deuteron wave-function is $P_{\Delta\Delta} = 0.2\%$ or slightly below. (There is no experimental information on the background beyond this level, if it is significantly lower, then greater sensitivity will be achieved, as the measurements will not be statistics limited at the level of $P_{\Delta\Delta} = 0.2\%$.) The $\Delta\Delta$ component may be expected to be an equal admixture of $\Delta^{++}\Delta^-$ and $\Delta^+\Delta^0$ states so the state of interest will occur only with a probability of $P_{\Delta\Delta}/2$, or roughly 10^{-3}. The $\Delta^{++}\Delta^-$ channel is chosen because the Δ^{++} decays almost 100% to two charged tracks making unambiguous reconstruction of back angle Δ^{++}'s possible.

The high luminosity available at CEBAF along with the large solid angle coverage of the CLAS spectrometer should make it possible to obtain far higher statistics on double-Δ production than have ever previously been obtained. This is critical to the success of the experiment because it will allow restrictive data-selection cuts to be applied to reject background. Two of the most important cuts (in addition to the restrictive exclusive kinematics described above) will be the selection of back-angle Δ's and the rejection of low momentum protons. All products from the interaction vertex will be strongly forward-peaked in the $\vec{q}$ direction while spectator Δ's should be almost isotropically distributed. Events of interest will be chosen to have an angle of at least 90° (and perhaps more) in the lab between the momentum of the spectator Δ and the $\vec{q}$ direction.

Previous measurements have shown the importance of rejecting spectator protons, so they do not accidentally combine with π^+ tracks from the production vertex to simulate a Δ^{++}. A serious potential source of background to the exclusive reaction channel could result from two-π production on the neutron. The accidental reconstruction of a backward-going π^+ with a spectator proton to give a mass in the Δ range could then simulate a spectator Δ^{++}. This background can be effectively eliminated, at modest cost to statistics, by requiring that the proton, which is a candidate for resulting from decay of a Δ^{++} spectator, have a momentum which is higher than would be expected for a spectator proton emerging from the breakup of the deuteron. A lower limit will be set on proton momentum. In the count rate estimates presented here, a conservative value, 250 MeV/c, has been used as the cutoff. In the actual analysis the cut will be chosen just high enough so the data in the lowest proton momentum bin do not show evidence of the asymmetric 'decay angle' distribution which results from mis-interpreting an accidental crossing as a decay.

For the purpose of estimating rates and acceptance, a simple Monte Carlo calculation has been performed for the reaction shown in Figure 2. The reaction was modeled in a pure spectator approximation in which the lab frame momentum vector of the Δ^{++} was taken to be the same after the interaction as before. The dynamics of the electron scattering interaction were modeled by a quasi-elastic interaction with the electromagnetic form-factors of the Δ^- simply being taken to be the same as the dipole fit to the proton form-factors. (It will be seen that the most important kinematic region is at low q, for which this approximation should be quite sufficient.)

To generate count rate distributions, Monte Carlo integration techniques were used to integrate the product of scattering cross section and reconstruction efficiency over electron scattering angles and to average over initial Δ momentum, struck Δ mass, spectator Δ mass, and decay angles for the struck and spectator Δ's. The initial Δ momenta were chosen according to the probability distribution shown in Figure 1, which is taken from the calculation of reference 1. Initial momentum directions were chosen isotropically, with the momenta of the spectator and interacting Δ being chosen opposite and equal. The final masses of the spectator and interacting Δ's were chosen independently according to Breit-Wigner distributions. The angular distribution for each of the Δ decays was chosen to be isotropic in the center of mass of the decaying Δ.

Effective scattering kinematics were found by imposing energy conservation in the spectator model, already described, then boosting the incident and scattered electron to the rest frame of the interacting Δ to determine the effective incident and scattered electron energies and the effective scattering angle. This boost introduced some dependence of the cross-section on the initial momentum of the struck Δ and therefore on the correlated spectator momentum. Thus the predicted final state spectator distribution is not isotropic.

The reconstruction efficiency required in the integration was found by running the FAST Monte Carlo[14] simulation of the CLAS spectrometer for the charged tracks of each event thus generated. Events were sorted according to which of the charged tracks were determined to be reconstructable, and separate histograms were accumulated for events with varying levels of reconstruction criteria. The FAST Monte Carlo also simulated the effects of finite resolution so distributions of reconstructed kinematic variables could be formed to include smearing resulting from the errors in reconstructing momenta and directions of the charged tracks.

For an incident beam energy of 4 GeV, Figure 3 shows the simulated distribution of cross section as a function of spectator momentum polar angle (relative to the beam direction) averaged over all other kinematic variables. This is the generated distribution with no effects of efficiency, acceptance, or resolution folded in. The kinematic cuts which have been imposed on the generated sample are a minimum lab-frame electron scattering angle of 8.5° and a minimum lab momentum, for the proton from Δ^{++} decay, of 250 MeV/c. Effects of energy loss and straggling in the target have not been included, but are expected to be negligible for a target whose diameter is matched to the narrow CEBAF beam. Each generated event has been weighted by the cross-section for quasi-elastic scattering. The observed anisotropy of the spectator distribution results from the boost to higher electron energy for forward-going spectators (interacting Δ is moving backward in the lab) and the reduced phase space available for the reversed initial momenta.

The cross-section scale given for all Monte Carlo simulations of the events of interest are the normalized cross-sections for scattering from the $\Delta^{++}\Delta^{-}$ component only. They must therefore be scaled by the probability of observation of that component, $P_{\Delta\Delta}/2$, to obtain meaningful cross-sections. While the value of $P_{\Delta\Delta}/2$ is, of course, unknown, it may be taken to be approximately 10^{-3} for the purpose of estimating count rates. This represents roughly the level of sensitivity which is the goal of the experiment. It is below most predicted values[1,2,3,4] and is half of the present experimental upper limit[11] of $P_{\Delta\Delta} < 0.4\%$. It should be noted that the error bars shown on the simulated distributions reflect only the statistical accuracy of the calculation and are not intended to reflect the statistical accuracy of the expected experimental data.

Figure 4 shows the distribution of reconstructed spectator Δ^{++} polar angle for those events for which both the proton and π^+ track could be reconstructed by the CLAS spectrometer. The spectrometer is assumed to be operating with the magnetic field direction reversed (i.e.. electrons bend away from the central axis). This is the optimal choice of field direction since the events of greatest interest will have the positive tracks in the back hemisphere and both negative tracks (electron and π^-) going forward. This choice of field will then tend to bend all charged tracks into the active detector region. The spectrometer is assumed to be running at full field strength. Comparison of Figure 4 with Figure 3 shows that, as expected, the efficiency for detection of the Δ^{++} is relatively constant for the region of greatest interest, backward-going Δ^{++}. The efficiency falls for small angle because the charged tracks have a higher probability of being bent out of the active region by the magnetic field.

Figure 5 shows the cross-section per bin for the reaction of interest in which the scattered electron is reconstructable along with both charged tracks from the Δ^{++} decay. To convert to count rates each bin must be multiplied by the luminosity and by the probability, $P_{\Delta\Delta}/2$, of finding the deuteron in the required state. For a standard high pressure deuterium target the CLAS[15] is expected to be able to handle a luminosity of $10^{34}/\mathrm{cm}^2/\mathrm{s}$. This is more conveniently expressed as 36/pb/hr. At back angles the cross section is seen to be about 1nb per bin or about 1 pb per bin when scaled by $P_{\Delta\Delta}/2$. The expected count rate for this reaction is then about 36 counts per bin of $\cos(\theta)$ per hour.

Figure 6 shows that the count rate per bin will be reduced by a little more than an additional factor of two if the data is also required to include a reconstructable π^- track from the decay of the Δ^-. Since background events arising from final state interactions are expected to have a strongly forward-peaked angular distribution, only events with back-angle Δ^{++}'s will be selected as signal. The angular cut will be chosen to maximize signal to background ratio and may restrict the region of interest to two or three angular bins such as those shown. A conservative rate estimate might be found by considering the last three bins in Figure 6, then, and would give approximately 36 events per hour.

Figure 7 compares the generated momentum distribution for the spectator Δ^{++} to the reconstructed distribution found by adding the resolution-smeared reconstructed p and π^+ tracks. The reconstructed distribution is seen to resemble that generated showing that there are no 'holes' in the acceptance as might be feared because of the cut on proton momentum.

Figure 8 shows the four-momentum transfer distribution. This distribution shows that the majority of the events seen involve small momentum transfer, $q^2 \approx 0.2 - 0.3$ $(GeV/c)^2$, as expected because of the decrease in the Δ form factor with increasing q^2. Observation of interactions with the pre-existing $\Delta\Delta$ component for several different bins of four-momentum transfer would allow the form-factor of the Δ^- to be mapped out. Perhaps more importantly, measurements at different q^2 can be compared to each other as a check of background contamination, which should enter differently at different momentum transfers. Figure 8 shows that the cross-section will fall by roughly two orders of magnitude as q^2 increases to 1 $(GeV/c)^2$. This distribution was generated using a dipole form-factor for the Δ^- while there are indications that the current distribution of the Δ may be more narrow in momentum space[16]. The count rate at back angles for $q^2 = 1$ $(GeV/c)^2$ may then be as low as 0.2/hr assuming the form-factor-squared of the Δ to be suppressed by a factor[17] of 0.67 relative to the dipole. Thus several hundred hours of running will be needed to acquire sufficient statistics in this q^2 range to allow accumulation of a spectator momentum distribution.

5) Background Estimates

As previously discussed, the dominant background in most previous experiments can be seen to result from accidental combinations of a spectator proton with a pion originating from the probe-neutron interaction. Many of the previous experiments were susceptible to contamination from such events if the invariant mass of the pair happened to fall into the Δ mass range. That background will be eliminated in the proposed experiment by requiring a minimum momentum for the proton which is beyond the range expected for spectator nucleons.

Benz and Söding[7] also eliminated most of this combinatorial background. However, they made no attempt to eliminate contributions from final state interactions of the general form represented in Figure 9. Rather, they argued that such diagrams constitute part of the signal. We disagree. It seems clear that a distinction must be drawn between that class of time-ordered diagrams in which the probe interacts with a pre-existing Δ, and those in which the probe interacts with a nucleon. The former contribute to the signal, in that they are related to the probability $P_{\Delta\Delta}$ that the probe will find the deuteron in a $\Delta\Delta$ configuration, while the latter constitute background events regardless of whether or not Δ's are excited during the interaction. (The fact that the Feynman formalism may unite the two classes of events into a single diagram does not imply that both contribute to the signal, rather it means that the time-ordered formalism is more appropriate for calculation of the separate contributions.) We classify the latter background events as final state interactions.

Restricting the class of events considered to exclusively those in which two Δ's are found in the final state should reduce the contribution from those events in which the virtual photon interacts with a nucleon to produce multiple mesons, one of which is re-absorbed to excite the spectator nucleon. Importantly, it will also eliminate events in which the struck nucleon is simply excited to a Δ which transfers its energy and isospin to the spectator by pion exchange. As discussed below, the angular distribution of Δ's originating from final state interactions may be expected to be more forward-peaked than true spectators. Therefore, angular cuts will also be used to select events of interest and reject final state interactions.

To estimate the effectiveness of angular cuts, it is useful to have some model of the kinematic distributions which are to be expected from final state interactions. In particular, intuition suggests that Δ's excited by final state interaction will peak strongly in the $\vec{q}$ direction, because that is the direction of motion of the hadronic system created by absorption of the virtual photon. It is important to determine the extent of this forward peaking. In order to study such kinematic distributions, a model was made of one contribution to the final state interaction background, as represented by the time-ordered diagram shown in Figure 10. The approximations and experimental input which have been used in this calculation are described in the appendix.

The resulting prediction for the angular distribution of the Δ^{++} produced in the final state interactions is shown in Figure 11. It is seen to be strongly peaked in the direction of $\vec{q}$, as might be expected. Note that the vertical scale in this case need not be scaled by the factor of $P_{\Delta\Delta}/2$ as the interacting particles are nucleons. Since the origin of this forward peaking is largely kinematic, it may have greater significance than just for the particular background channel which has been calculated. Any background which originates from a final state interaction may be expected to exhibit similar forward peaking. This distribution shows only the Δ which is excited by final state interaction. The 'struck' particle's laboratory distribution is even more strongly forward peaked and can be entirely neglected at back angles.

Figures 12 a) and b) compare this calculated final state interaction background to the calculated quasi-elastic signal, which has been scaled by assuming $P_{\Delta\Delta}/2 = 0.1\%$. The background model should give more reliable prediction of the shape of the background than of its magnitude. As described in the appendix, the calculation is probably an overestimate for the single channel considered. The two figures represent the different possible selection criteria for reconstruction of the events. Figure 12a) is for the looser requirement, in which only the electron and the decay products of the Δ^{++} are required (the Δ^{-} being reconstructed by missing mass). In Figure 12b) the π^{-} from the Δ^{-} decay is also required to be reconstructable. The background is seen to decrease rapidly with increasing Δ^{++} polar angle, even beyond 90°. This suggests that a selection can be made of an optimal range of polar angle which will minimize the contamination from final state interactions.

One kinematic difference between true quasi-elastic events and final state background is seen in Figure 13. Not surprisingly, the majority of the strength for final state interaction is seen to lie at low 3-momentum transfer. This provides a tool for suppression of the background. If the kinematic behavior of this simple calculation is assumed to carry over to more sophisticated calculations, then an enhancement in the signal to background ratio of more than a factor of two can be achieved by selecting only events with high q. Since no previous experiment has been able to benefit from such a cut, this should contribute to reduction of the background of the present experiment compared to previous upper limits.

Proper interpretation of the measured data will require a method (preferably with minimal model dependence) of estimating the fraction of the observed $\Delta\Delta$ pairs which originate from final state interactions. For this purpose, the fact that the background may be expected to dominate at forward angle is a virtue. More realistic calculations of the background can be tested against their ability to predict the observed rate and angular distribution at forward angle. If necessary, they can even be adjusted to fit the observed forward angle peak. All that will be required of the final state calculations then will be a reliable extrapolation to back angles.

Kinematic differences may allow another check of the degree of contamination of the $\Delta\Delta$ data by final state interactions, albeit a somewhat model dependent one. Figure 14 shows a comparison between the expected momentum distributions for the true quasi-elastic spectator events and that for events resulting from final state interactions. For Δ^{++} momenta above 600 MeV/c, spectator events are seen to dominate. Thus the onset of a high momentum component to the Δ^{++} momentum distribution, at back angles, may indicate true quasi-elastic production from a $\Delta\Delta$ component in the deuteron. Unfortunately, extraction of $P_{\Delta\Delta}$ from just this information would be subject to model dependence in the calculation of the momentum distribution of the pre-existing Δ's and in any distortion of the momentum distribution of the spectators. However, this does offer the possibility of some sensitivity, even if $P_{\Delta\Delta}$ is so small that final state interactions dominate at back angles. The fraction of the Δ^{++}'s in this high momentum 'tail' may also be used as a method of determining whether background contamination is less of a problem in the high q^2 portion of the data.

6) Trigger Considerations

Maximizing the acceptance of the CLAS for the topology of interest requires running with reversed field. Furthermore, the majority of the data results from relatively small angle electron scattering. This raises the question of whether trigger problems will result because the Cerenkov detector optics at small angle has been optimized for electrons which are being bent toward the axis.

Fortunately, the events of particular interest are sufficiently well-defined that it should be possible to define a highly sensitive trigger without requiring information from the Cerenkov counters. Such a trigger could then be used to enrich the collected data sample, should pre-scaling be required on the more general triggers. The shower counters, or even ad hoc trigger scintillators could be used to detect the small angle electrons. The additional requirement of two positive tracks at large angle (the proton and π^+ from the Δ^{++} decay) should reduce this component of the trigger rate to a quite low level. Figure 15 shows the angular distributions for the proton and π^+ resulting from detected events for which the polar angle of the reconstructed Δ^{++} momentum is over 90°. A cut at 45° or even 60° for each particle would have negligible effect on the efficiency while greatly limiting the contribution of this trigger to the total rate. A less restrictive trigger (still requiring two positive tracks as well as the electron) would also be pre-scaled in, of course, to sample the forward-angle distribution.

Alternately, running at a reduced field strength could obviate the need for any trigger pre-scaling. This would be considered as a possibility to allow other experiments to run in parallel. Additional study would be required before making a decision to run at reduced field, but preliminary indications are that neither acceptance nor reconstruction resolution would be unacceptably degraded at half field.

7) Beam Time Request

We request 20 days (480 hours) of running at 4 GeV incident electron energy with a deuterium target in the CLAS spectrometer running at full field strength in the reversed direction. This will give high statistics (approx. 17000 counts, for $P_{\Delta\Delta}/2 = 0.1\%$) for back angle Δ^{++} production, allowing tight background rejection cuts to be applied and still giving sufficient statistics to form spectra of spectator momentum, decay angles, etc. Data for higher q^2 bins will be accumulated simultaneously. The requested running time will be sufficient to make measurements in several bins of q^2, approaching $q^2 = 1$ $(GeV/c)^2$. Statistics in the final bin (approx. 100 counts of signal) will suffice for a test of feasibility for future running at higher q^2.

We also request 2 days of running at each of 2 GeV and 3 GeV. This will provide information on the behavior of background sources, aiding in more realist modeling for estimation and subtraction of backgrounds. It will also provide important input as to whether 4 GeV is the optimal energy for maximizing signal to noise, as expected from Monte Carlo simulation. In the unlikely circumstance that background rates are found to fall less rapidly, with increasing beam energy, than expected signal cross-sections, we may modify our running plan to use a more advantageous beam energy.

An additional total of 1 day of running on a blank target is requested (to be interleaved with data-taking runs).

The total beam time requested is <u>25 days</u> <u>(600 hours)</u>.

Appendix

We describe here a simple calculation which was made to determine the expected kinematic distribution of Δ's arising from final state interactions. To estimate the extent of the forward-peaking of such background, we calculated the contribution of the time-ordered diagram shown in Figure 10. Two separate interaction vertices are connected by an off-shell intermediate state. At the first vertex, the electromagnetic interaction excites a nucleon to a virtual Δ. At the second vertex, the virtual Δ interacts with the spectator nucleon to leave two Δ's in the final state.

Evaluation of the amplitude as a second-order perturbation involves expanding the initial deuteron wave function in terms of a complete state of nucleon momentum eigenstates. In principle this loop thus introduces an integral into the evaluation of the amplitude. This complication can be bypassed in the factorization approximation, however, if the slight dependence of the two interaction vertices upon the initial momentum of the nucleons is neglected. The sum over the complete set of momentum eigenstates (using discreet, box normalized wave functions) then sums up only the momentum components of the deuteron wave function. This sum, which is just the Fourier transform of the momentum-space wave function, is then recognized to be the deuteron spatial wave function evaluated at the origin (within a normalization factor). $|A|^2$ then is proportional to the particle density of the deuteron at the origin. Because of the hard core, this would result in a substantial suppression of the background, if taken literally. The fact of such a large suppression, however, probably belies the original approximation that the vertices are strictly independent of nucleon momentum. A reasonable compromise approximation is to replace the particle density at the origin by the average particle density near the origin. A <u>worst-case</u> assumption was made to choose the distance over which to average. The density was averaged over that sphere which has the largest average particle density. For a reasonable deuteron wave function[18] the radius of this sphere was 1.3 fm. This treatment may result in the evaluation of this background contribution being significantly overestimated[19].

The required matrix element for the first vertex at a given q^2 was extracted from a phenomenological fit[20] to electro-excitation cross sections on the proton by dividing out the phase space. The matrix element for $p\,\Delta \rightarrow \Delta\,\Delta$ was modeled as being the same as that for $p\,p \rightarrow n\,\Delta^{++}$ which was also extracted from experimental data[21] by dividing out phase space. The data was interpolated/extrapolated to kinematics other than those measured by approximating the Lorentz invariant matrix element, $s \times p_{cm}{}^2 \times (d\sigma/dt)$, as a universal function of t. The scaled data is shown in Figure 16 and this is seen to be a reasonable approximation over a large kinematic range.

The resulting prediction for laboratory angular distribution of the Δ^{++} is shown in Figure 11 and is seen to be strongly peaked in the direction of $\vec{q}$, as might be expected. This forward peaking offers the possibility of choosing an optimal kinematic range in which these background contributions are small compared to the signal. It also means that predictions of these background contributions can be unambiguously tested in the small angle region, in which they dominate.

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Figure Captions

Figure 1) The momentum distribution for the $\Delta\Delta$ component of the deuteron, as predicted by reference 1. The high-momentum tail results from a large contribution of the ^7D state.

Figure 2) Diagram representing the quasi-elastic mechanism leading to a two-Delta final state. The virtual photon couples to a pre-existing Δ while the second Δ is a spectator which retains its initial momentum projection. The subscripts S and X are used to label the spectator and interacting Δ's.

Figure 3) The generated angular distribution of Δ^{++} from the calculation of the reaction shown in Figure 2. θ is the angle between the incident beam direction and the momentum vector of the Δ^{++}. Events are included in the distribution only if the electron scattering angle exceeds 8.5° and the momentum of the proton (resulting from the decay of the Δ^{++}) exceeds 250 MeV/c.

Figure 4) The same angular distribution as in Figure 3 is shown for only those events which are found to have reconstructable proton and π^+ from the decay of the Δ^{++}. A track is considered to be reconstructable if the FAST Monte Carlo shows it to have hits on all three CLAS superlayers. Note that the angle which is binned is reconstructed from the tracks with the effects of finite resolution folded in. The angle, θ, is measured relative to the beam direction to clearly display the effects of the CLAS acceptance.

Figure 5) The angular distribution of the spectator Δ^{++} as measured from the direction of $\vec{q}$, the momentum transferred by the electron. Events from the distribution in Figure 3 are included in this distribution if they are determined to have reconstructable tracks for the proton, π^+, and the electron. This is the minimal level of reconstruction required for the data in the present proposal. This angle, θ_{Sq}, may be expected to have more sharply defined background distributions than θ, because of the tendency of particles from the photon interaction to move in the direction of $\vec{q}$.

Figure 6) Same as Figure 5, except the included events are subject to the additional constraint that the π^- from the Δ^- decay must also be reconstructable.

Figure 7) a) The shape of the generated Δ^{++} spectator momentum distribution found from calculation of the reaction shown in Figure 2.

b) The shape of the reconstructed distribution, which is seen to be similar, for events in which the proton and π^+ from the decay of the Δ^{++} are reconstructable.

Figure 8) The distribution as a function of $|q^2|$ found from calculation of the reaction shown in Figure 2. q is the 4-momentum transferred by the electron.

Figure 9) Diagram representing a class of events which was included as signal in reference 7. The diagram is re-drawn from reference 7.

Figure 10) Time ordered diagram representing a potential contribution to the background of the present experiment. At the first interaction vertex the virtual photon excites a virtual Δ. At the second interaction vertex a final state interaction between the remaining nucleon and the virtual Δ results in two Δ's in the final state. Although neither Δ is a spectator, one is labeled as Δ_S to signify that it has to potential to mimic a spectator.

Figure 11) The angular distribution of the Δ^{++} from the final state interaction represented by Figure 10, as measured from the direction of $\vec{q}$, the momentum transferred by the electron. This angle, θ, may be expected to have more sharply defined background distributions than the angle measured from the beam direction, because of the tendency of particles from the photon interaction to move in the direction of $\vec{q}$.

Figure 12) a) Calculated angular distributions, relative to the $\vec{q}$ direction, for the quasi-elastic reaction shown in Figure 2 (plotted as unconnected data points) and for the final state interaction shown in Figure 10 (plotted as connected x's). Note that the quasi-elastic points have been scaled by assuming a value of $P_{\Delta\Delta}/2 = 0.1\%$. The abrupt change in error-bar size at $\theta=90°$ is purely an artifact of the Monte Carlo statistics which were chosen to concentrate on back angles. For both the signal and background, events are included in this distribution only if the electron, proton, and π^+ are reconstructable (permitting reconstruction of the Δ^{++} and Δ^-).

b) Same as a) but the π^- track from the decay of the Δ^- is also required to be reconstructable.

Figure 13) a) Calculated distribution as a function of 3-momentum transfer for the quasi-elastic reaction shown in Figure 2. Events are included in this distribution only if the electron, proton, and π^+ are reconstructable and the direction of the Δ^{++} is in the backward hemisphere ($\cos(\theta)<0$).

b) Same as a) but for the final state interaction background shown in Figure 10.

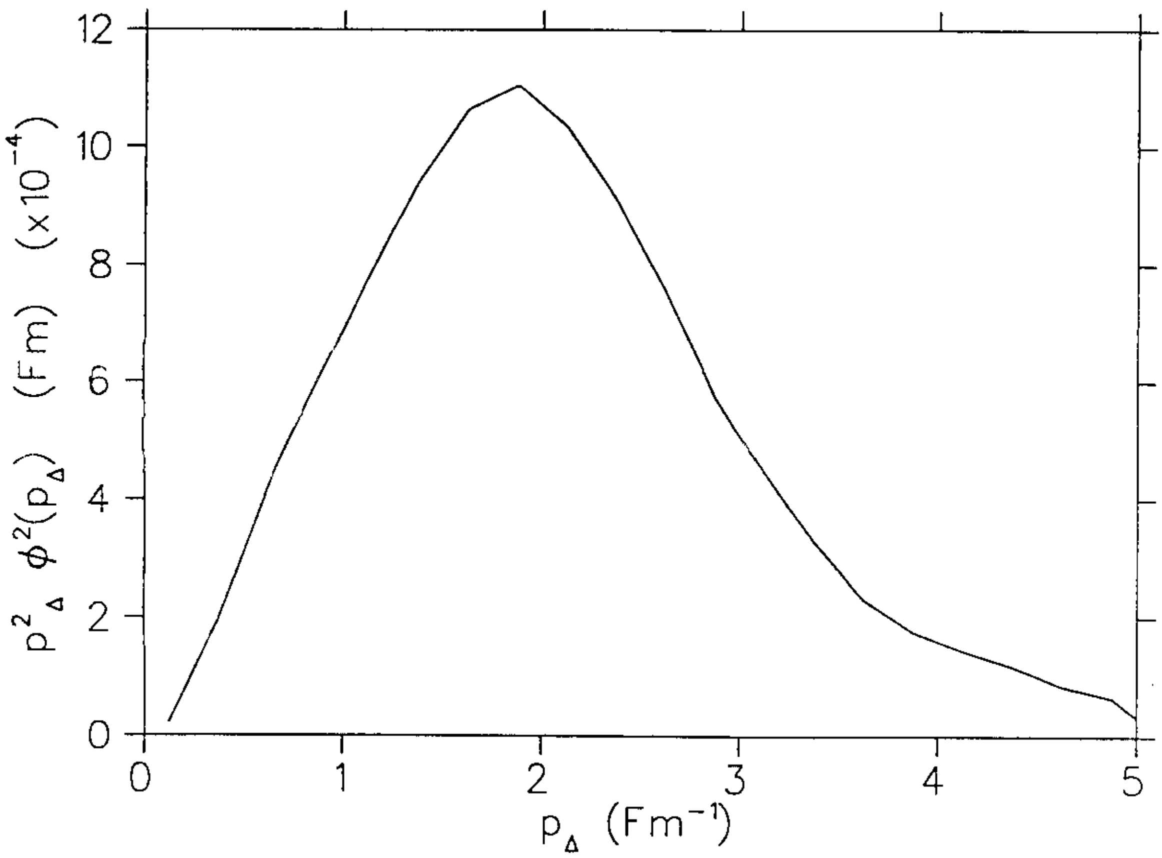
Figure 14) a) Calculated distribution as a function of Δ^{++} momentum for the quasi-elastic reaction shown in Figure 2. Events are included in this distribution only if the electron, proton, and π^+ are reconstructable and the direction of the Δ^{++} is in the backward hemisphere ($\cos(\theta)<0$).

b) Same as a) but for the final state interaction background shown in Figure 10.

Figure 15) a) Calculated distribution as a function of lab angle, , of the proton resulting from the decay of the Δ^{++} for the quasi-elastic reaction shown in Figure 2. Events are included in this distribution only if the proton, and π^+ are reconstructable and the direction of the Δ^{++} is in the backward hemisphere. Examination of the distribution shows a negligible effect from a trigger requirement of $\theta_p > 45°$ ($\cos(\theta_p)<.71$), and only a slight effect from requiring $\theta_p > 60°$ ($\cos(\theta_p)<.5$).

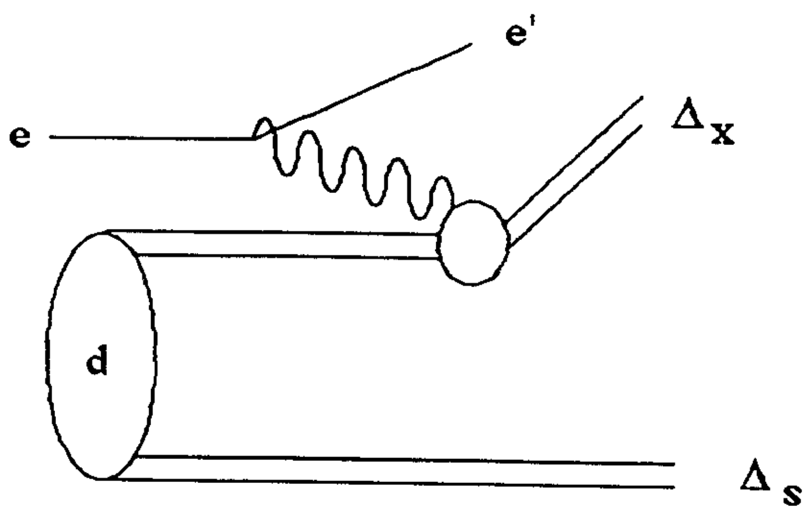
b) Same as a), but for the π^+, rather than the proton, from the decay of the Δ^{++}.

Figure 16) Data for the reaction $p\,p \rightarrow n\,\Delta^{++}$, taken from reference 21, is displayed for 4 different lab momenta to show that $s \times p_{cm}^2 \times d\sigma/dt$ is approximately a universal function of t. This approximation was used in scaling the data to the kinematic appropriate to each event in estimating the background contribution from the reaction represented by Figure 10. The matrix element extracted from this data was used as an approximation in place of the matrix element for the reaction, $p\,\Delta^0 \rightarrow \Delta^{++}\,\Delta^-$.



12
10
8
6
4
2
0
0
1
2
3
4
5
$p_\Delta^2\ \phi^2(p_\Delta)$ (Fm) $(\times 10^{-4})$
p_Δ (Fm^{-1})

Fig. 1



e
e'
Δ_X
d
Δ_S

Fig. 2

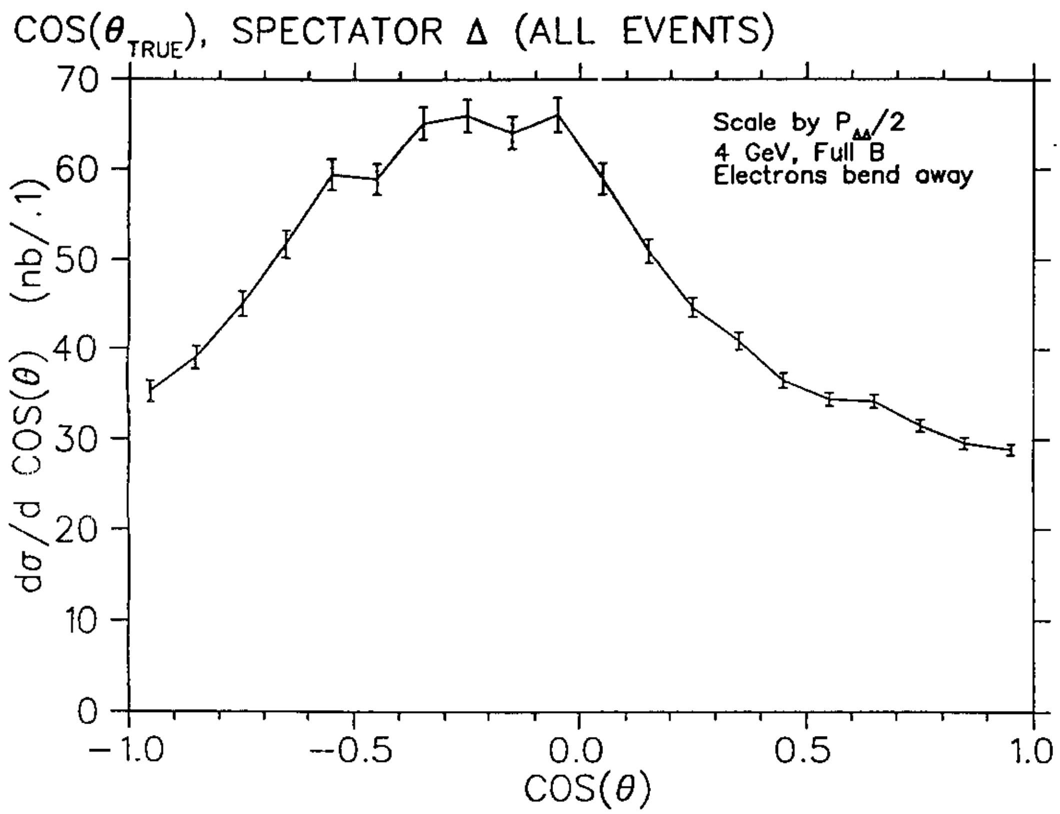

COS(θ_{TRUE}), SPECTATOR Δ (ALL EVENTS)
Scale by $P_{\Delta\Delta}/2$
4 GeV, Full B
Electrons bend away
dσ/d COS(θ) (nb/.1)
COS(θ)
70
60
50
40
30
20
10
0
−1.0
−0.5
0.0
0.5
1.0

Fig. 3

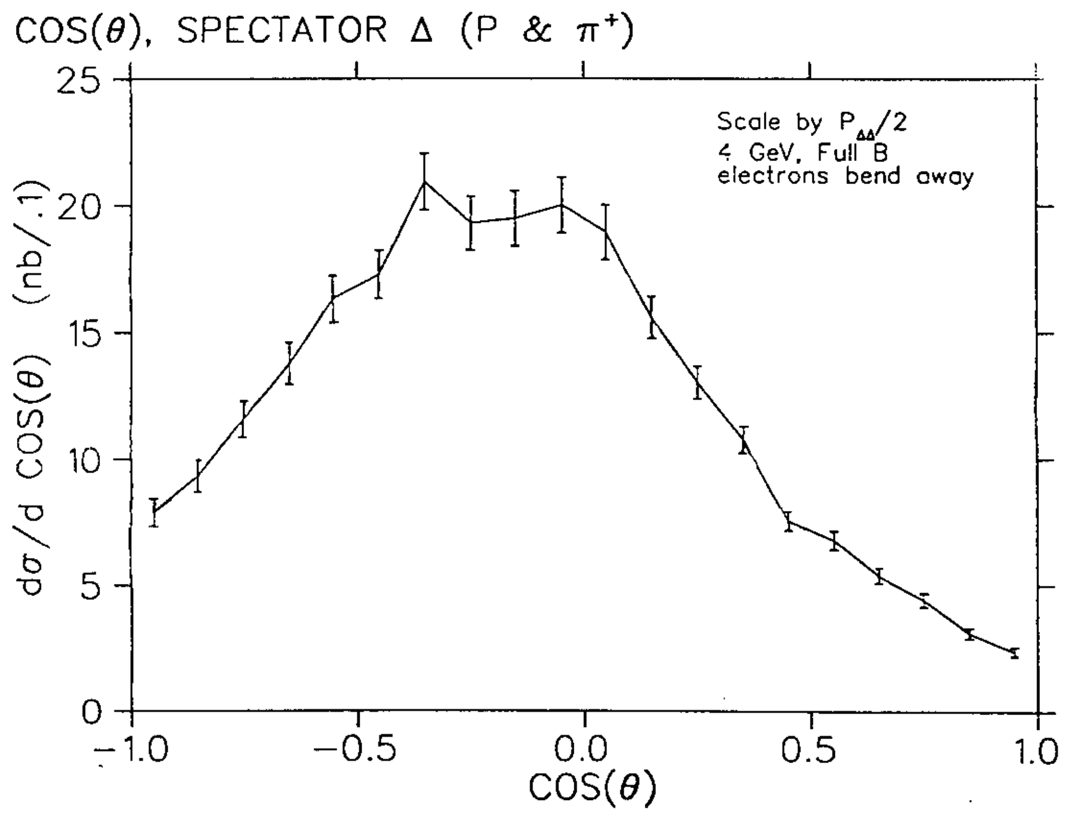

COS(θ), SPECTATOR Δ (P & π^+)
Scale by $P_{\Delta\Delta}/2$
4 GeV, Full B
electrons bend away
dσ/d COS(θ) (nb/.1)
COS(θ)
25
20
15
10
5
0
−1.0
−0.5
0.0
0.5
1.0

Fig. 4

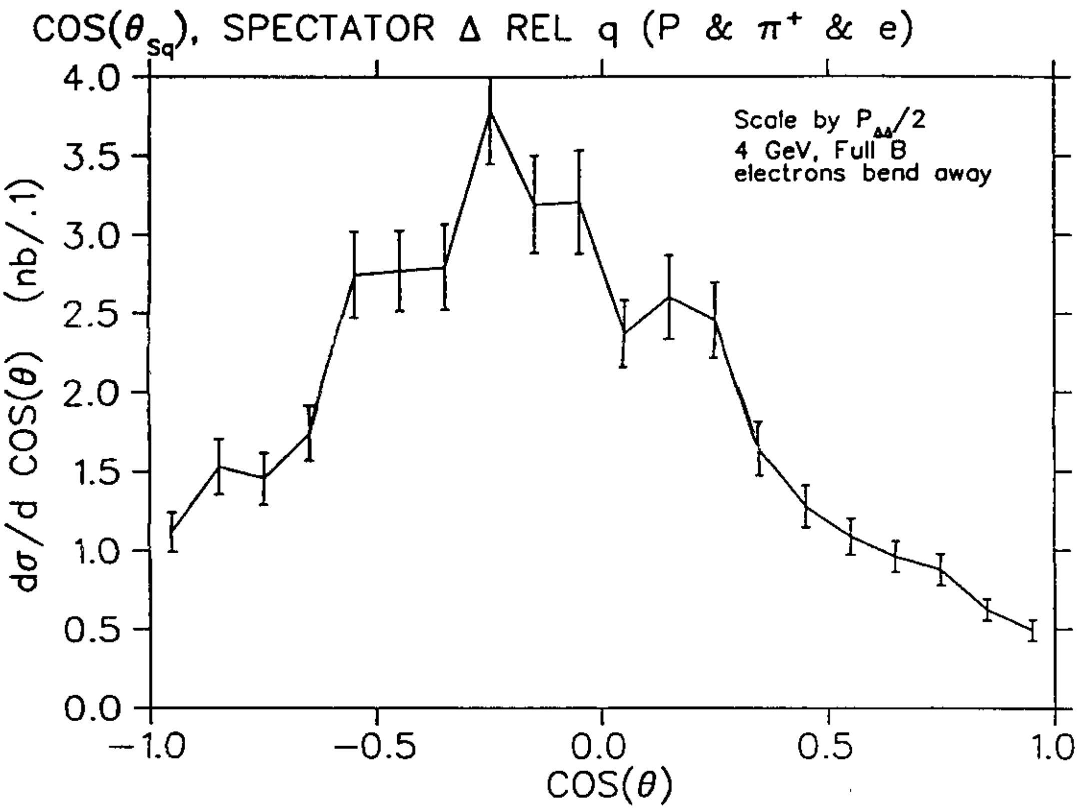

COS(θ_{Sq}), SPECTATOR Δ REL q (P & π^+ & e)
Scale by $P_{\Delta\Delta}/2$
4 GeV, Full B
electrons bend away
dσ/d COS(θ) (nb/.1)
COS(θ)

Fig. 5

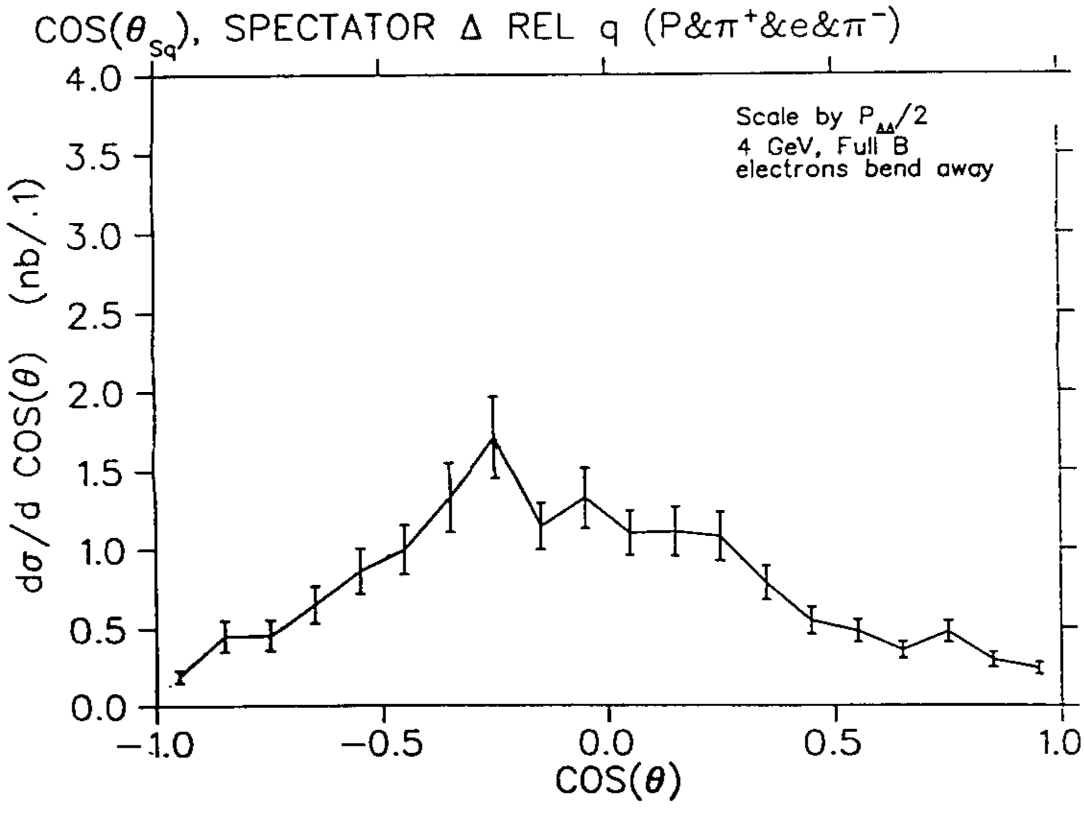
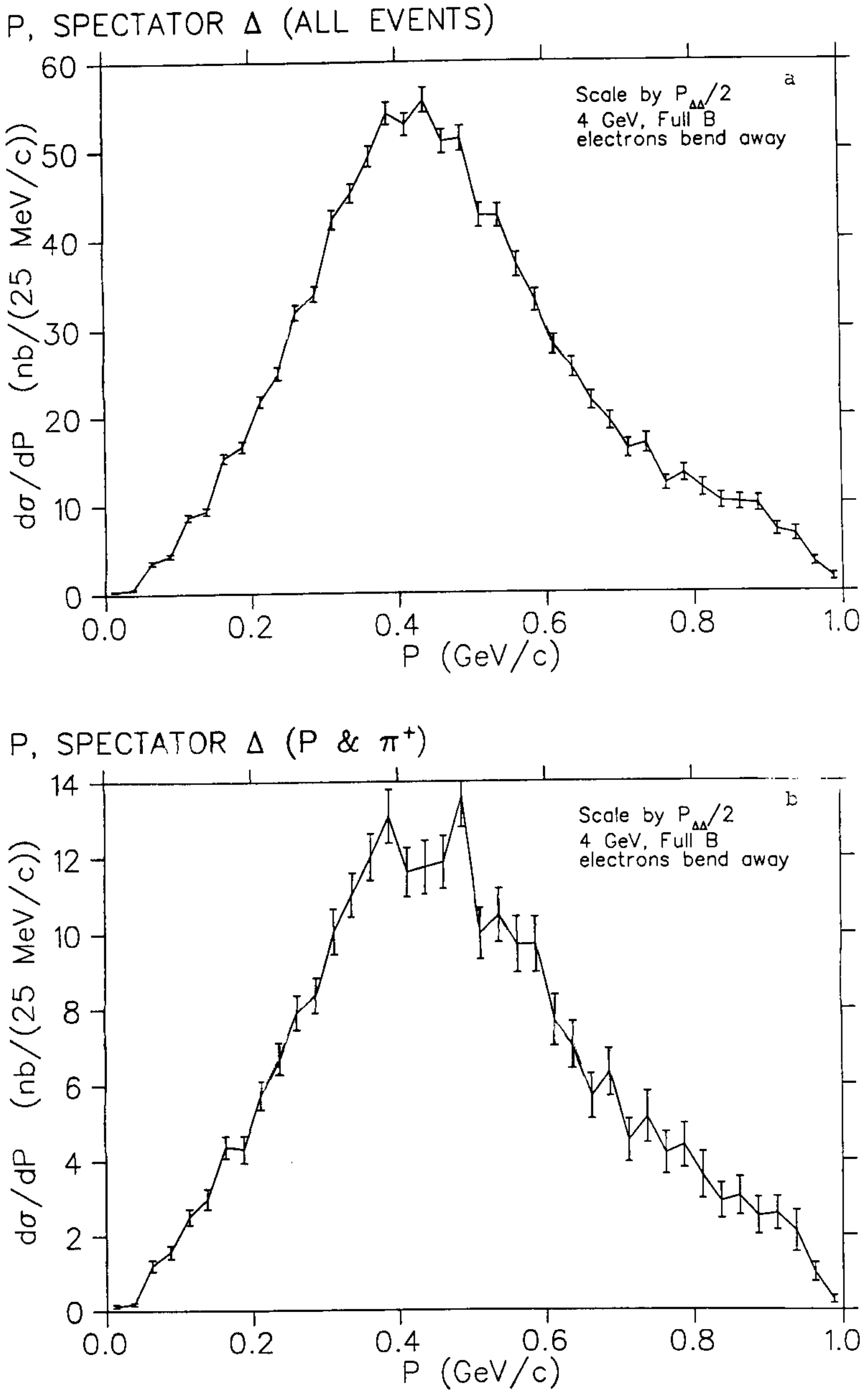
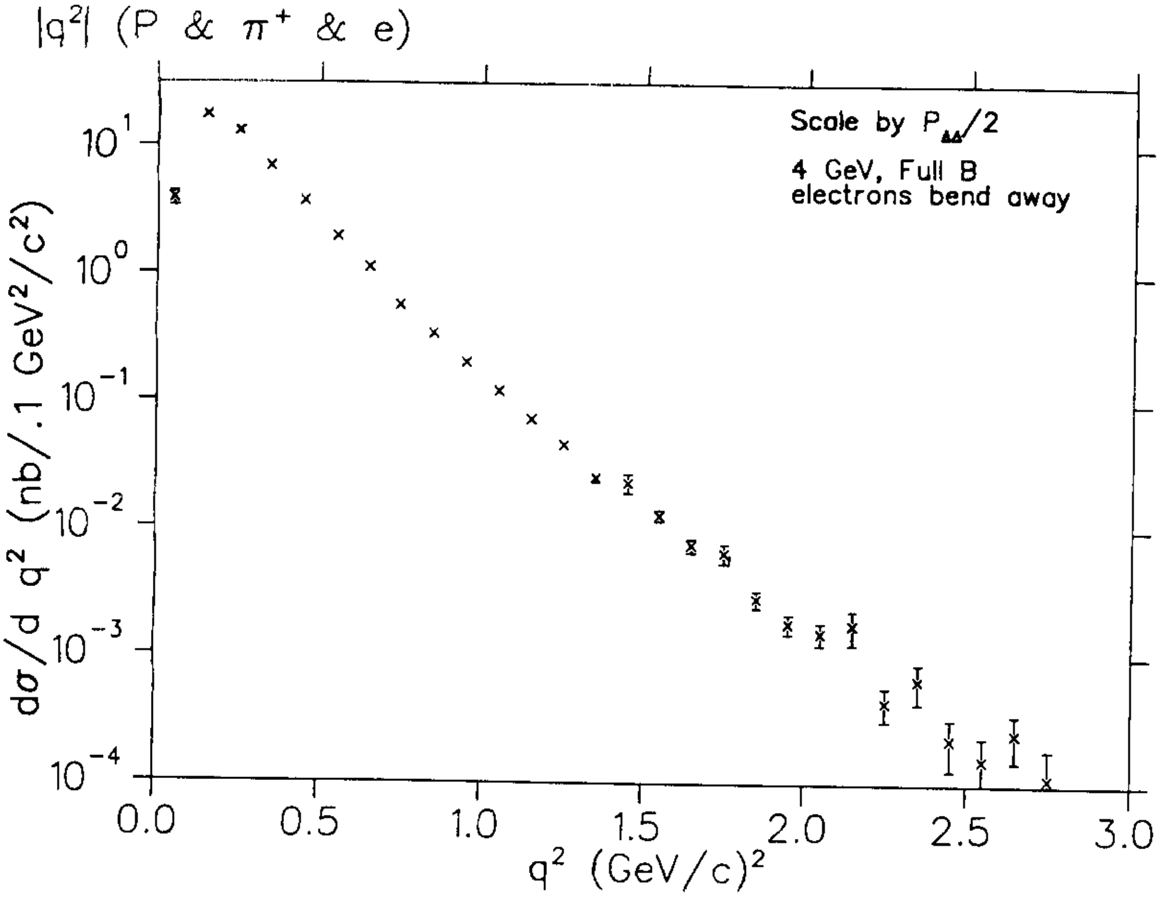

COS(θ_{Sq}), SPECTATOR Δ REL q (P&π^+&e&π^-)
Scale by $P_{\Delta\Delta}/2$
4 GeV, Full B
electrons bend away
dσ/d COS(θ) (nb/.1)
COS(θ)

Fig. 6



P, SPECTATOR Δ (ALL EVENTS)
Scale by P_ΔΔ/2
4 GeV, Full B
electrons bend away
a
dσ/dP (nb/(25 MeV/c))
P (GeV/c)
P, SPECTATOR Δ (P & π+)
Scale by P_ΔΔ/2
4 GeV, Full B
electrons bend away
b
dσ/dP (nb/(25 MeV/c))
P (GeV/c)

Fig. 7



|q²| (P & π⁺ & e)
Scale by $P_{\Delta\Delta}/2$
4 GeV, Full B
electrons bend away
$d\sigma/d\ q^2$ (nb/.1 GeV²/c²)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.0
0.5
1.0
1.5
2.0
2.5
3.0
q^2 (GeV/c)²

Fig 8

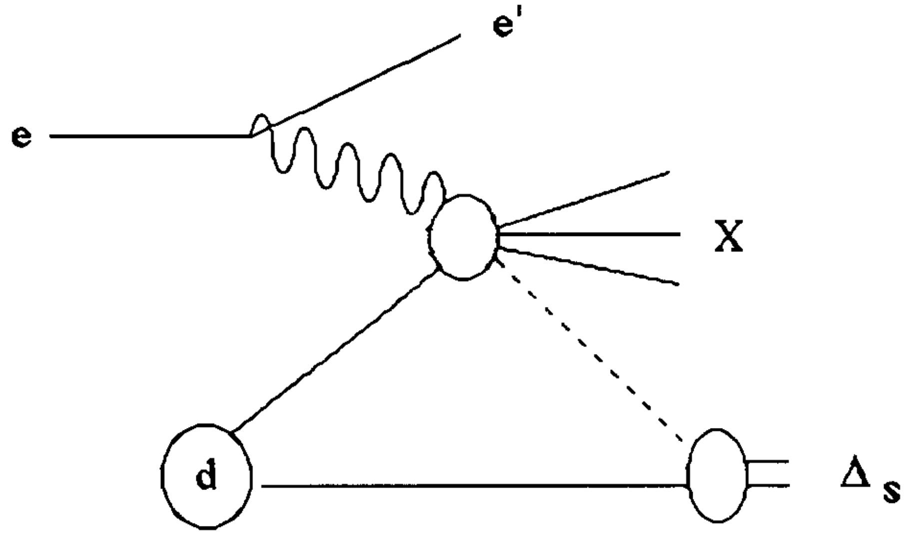


Fig. 9

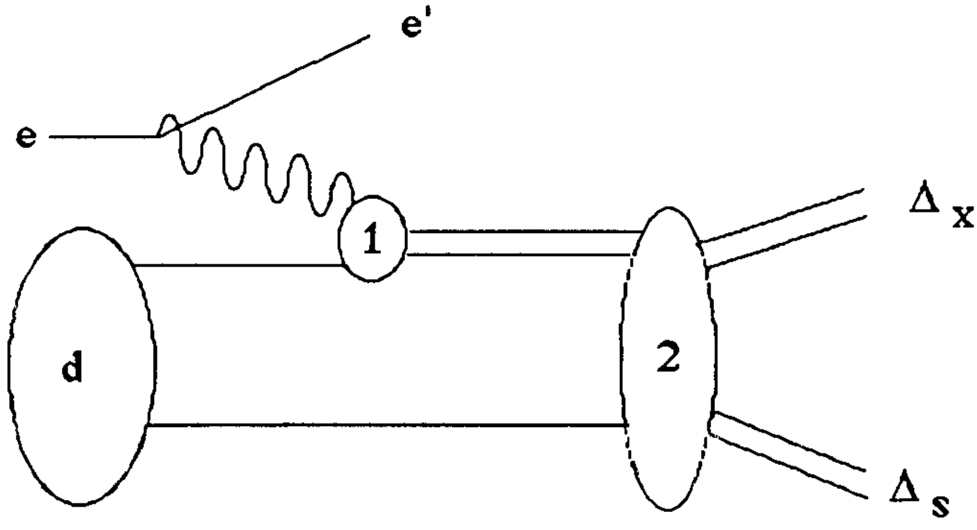


Fig. 10

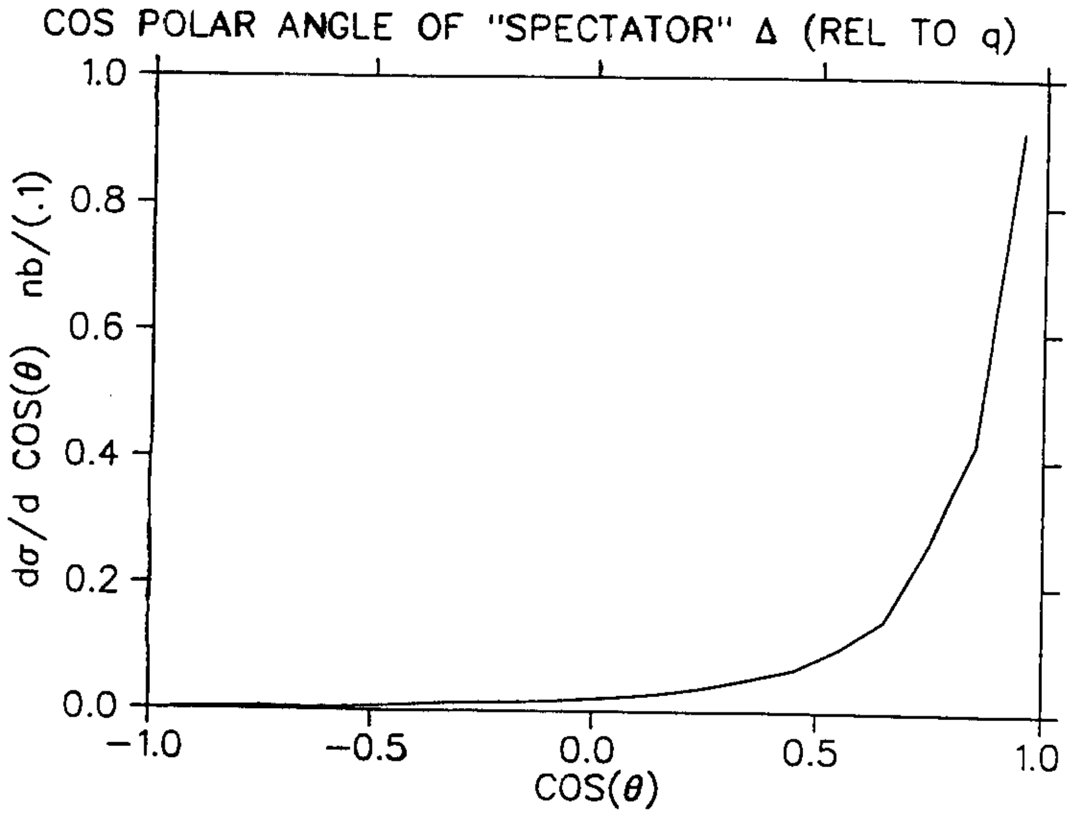
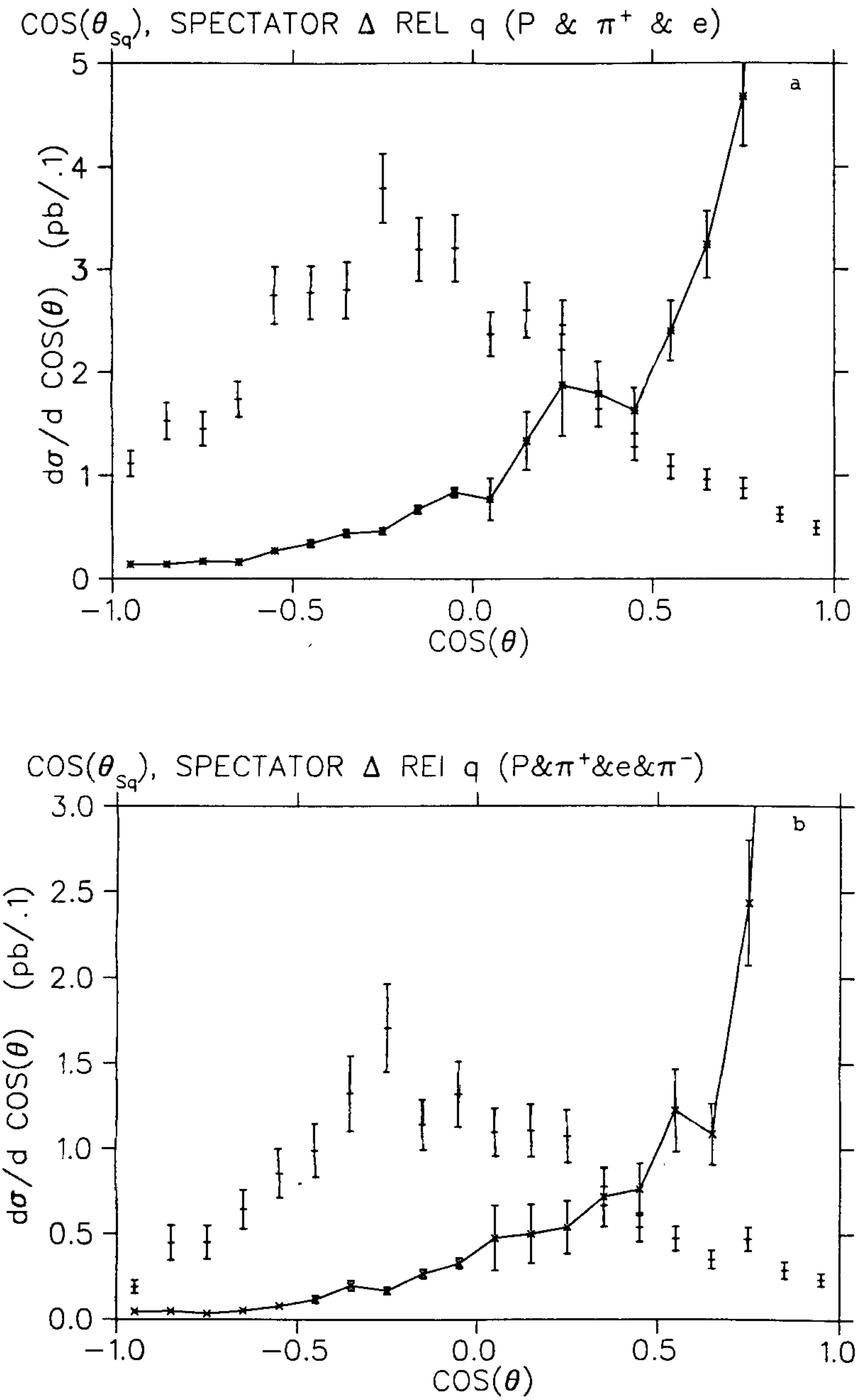
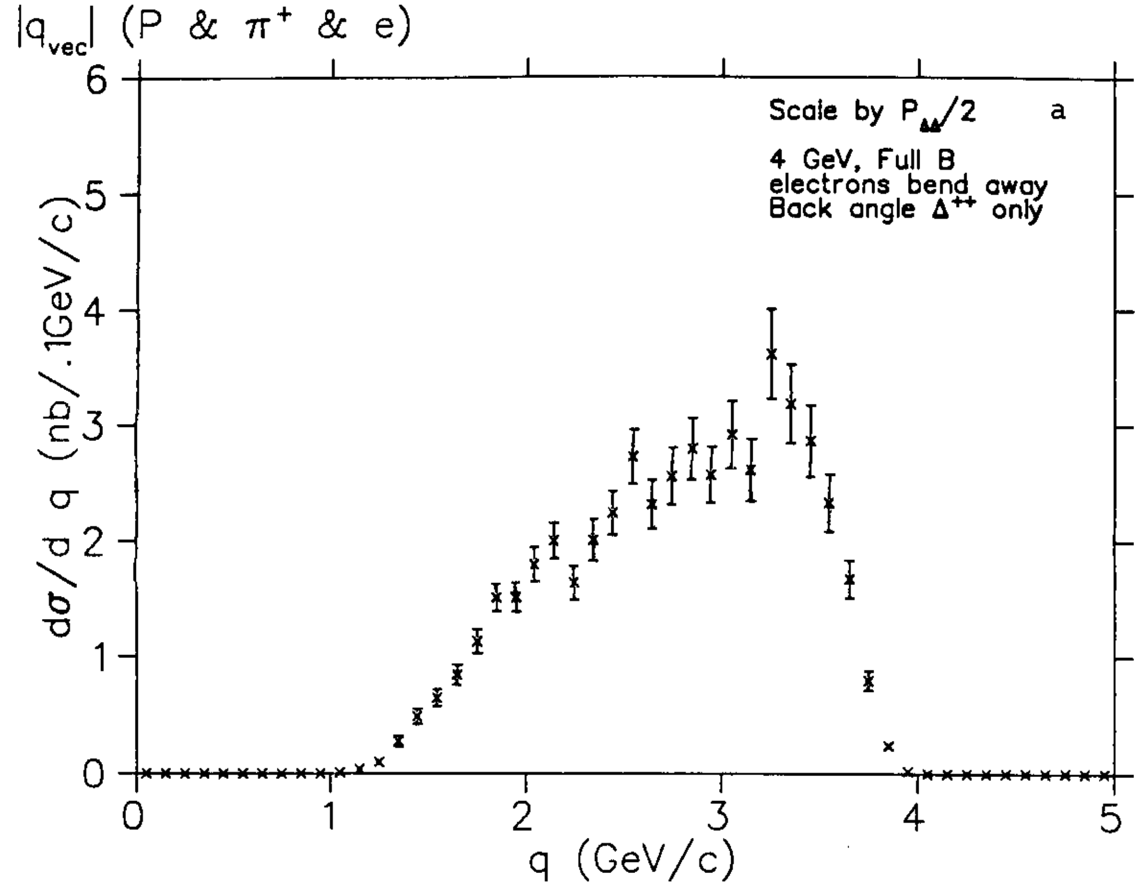

COS POLAR ANGLE OF "SPECTATOR" Δ (REL TO q)
1.0
0.8
0.6
0.4
0.2
0.0
dσ/d COS(θ) nb/(.1)
−1.0
−0.5
0.0
0.5
1.0
COS(θ)

Fig. 11

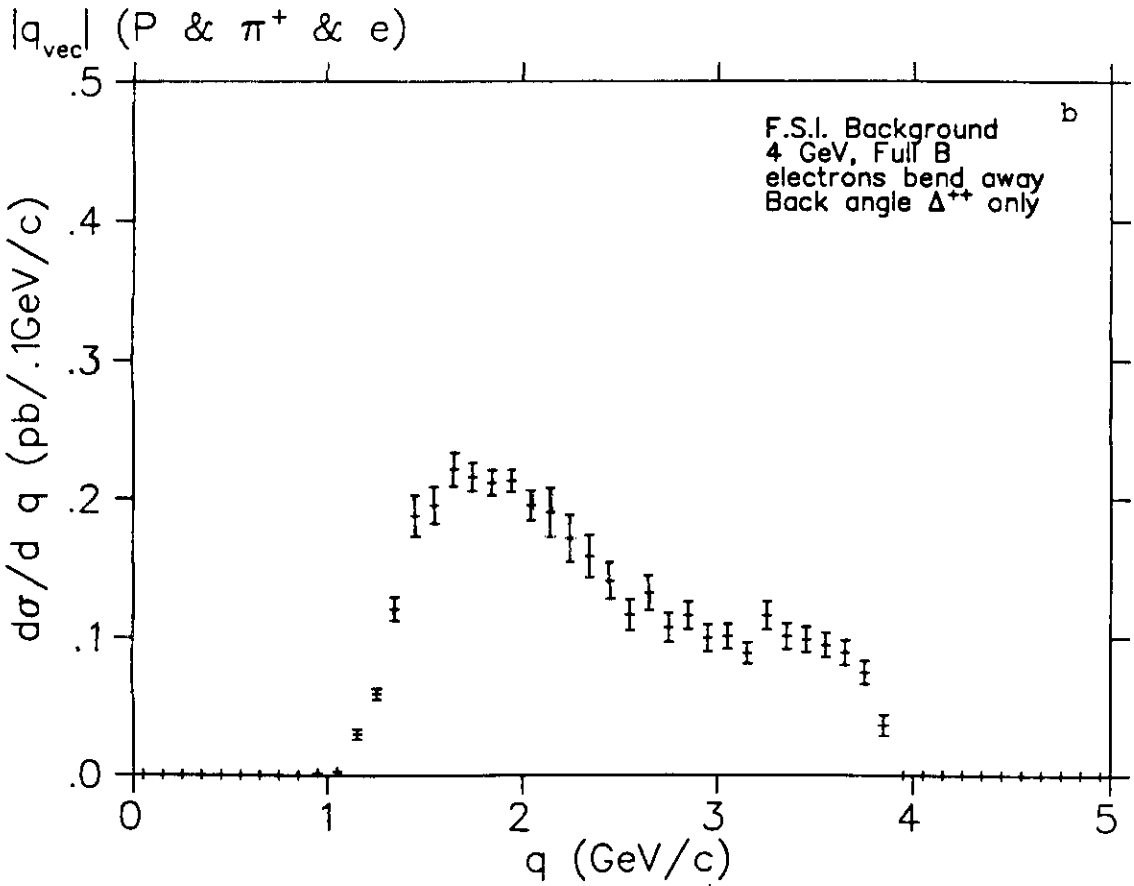


COS(θ_{Sq}), SPECTATOR Δ REL q (P & π^+ & e)
a
$d\sigma/d\ COS(\theta)$ (pb/.1)
COS(θ)
COS(θ_{Sq}), SPECTATOR Δ REl q (P&π^+&e&π^-)
b
$d\sigma/d\ COS(\theta)$ (pb/.1)
COS(θ)

Fig. 12

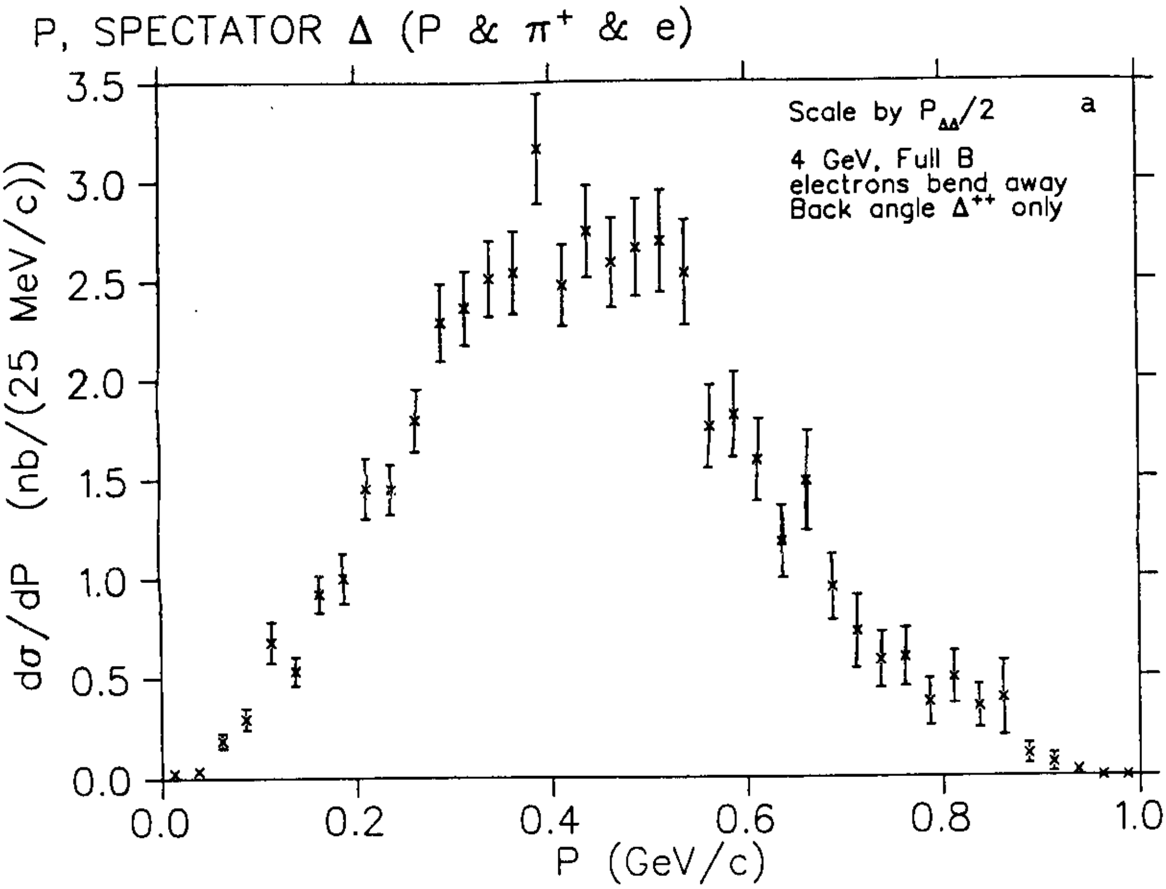


|q_vec| (P & π⁺ & e)
Scale by P_ΔΔ/2
a
4 GeV, Full B
electrons bend away
Back angle Δ⁺⁺ only
dσ/d q (nb/.1GeV/c)
q (GeV/c)
0
1
2
3
4
5
6



|q_vec| (P & π⁺ & e)
F.S.I. Background
b
4 GeV, Full B
electrons bend away
Back angle Δ⁺⁺ only
dσ/d q (pb/.1GeV/c)
q (GeV/c)
.0
.1
.2
.3
.4
.5
0
1
2
3
4
5

Fig. 13


P, SPECTATOR Δ (P & π⁺ & e)
Scale by P_ΔΔ/2
a
4 GeV, Full B
electrons bend away
Back angle Δ⁺⁺ only
dσ/dP (nb/(25 MeV/c))
P (GeV/c)

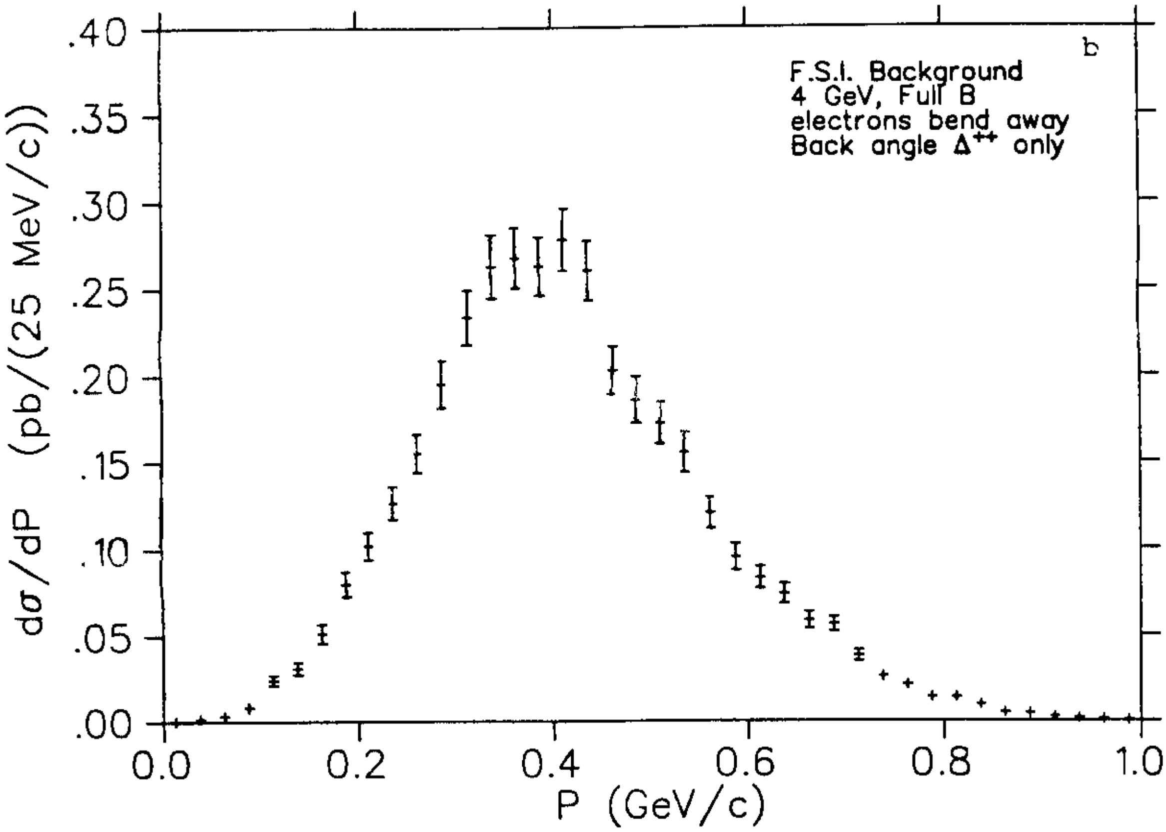

b
F.S.I. Background
4 GeV, Full B
electrons bend away
Back angle Δ⁺⁺ only
dσ/dP (pb/(25 MeV/c))
P (GeV/c)

Fig. 14

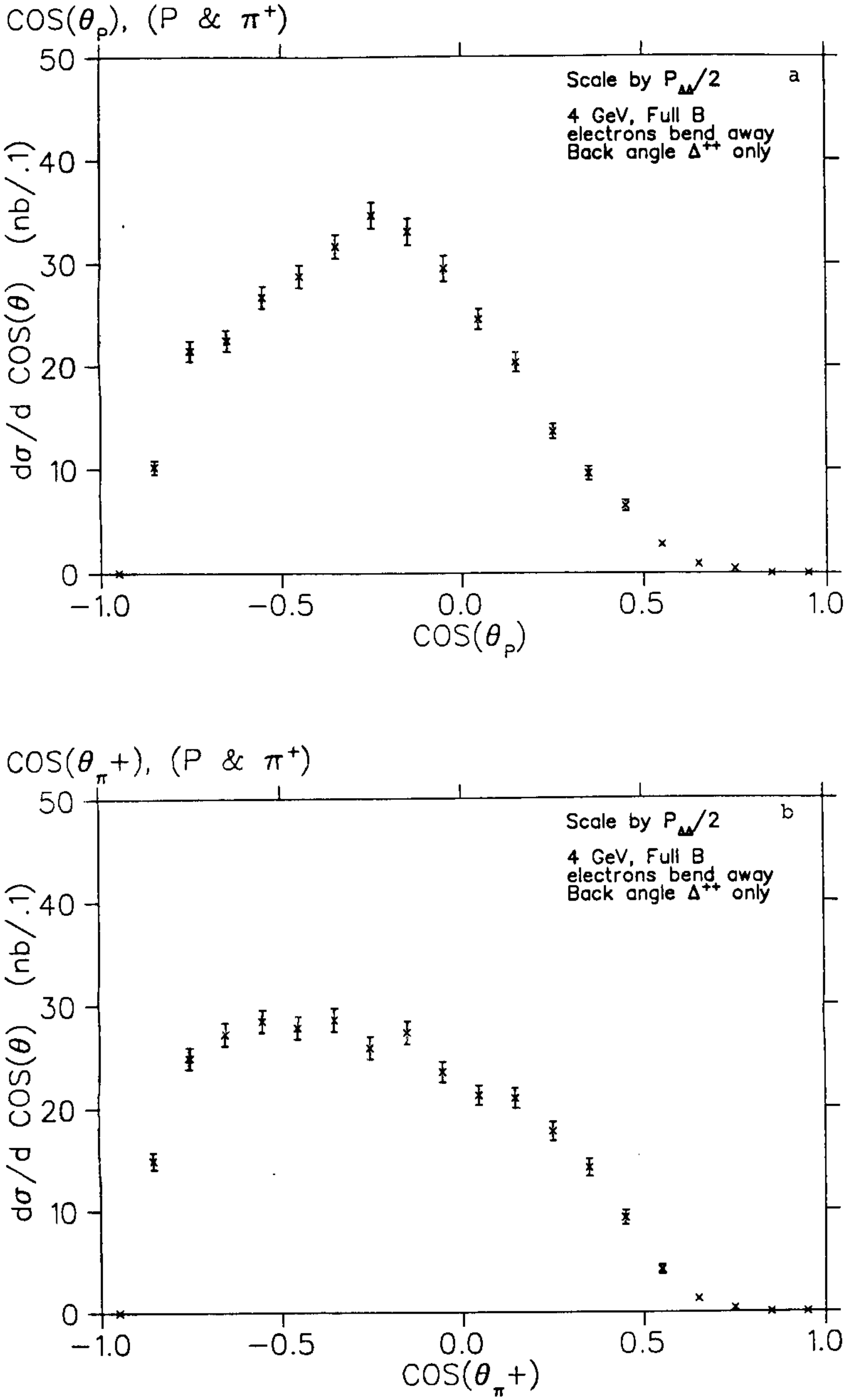

COS(θ_p), (P & π^+)
Scale by $P_{\Delta\Delta}/2$
a
4 GeV, Full B
electrons bend away
Back angle Δ^{++} only
$d\sigma/d\,COS(\theta)$ (nb/.1)
COS(θ_p)
COS(θ_{π}+), (P & π^+)
Scale by $P_{\Delta\Delta}/2$
b
4 GeV, Full B
electrons bend away
Back angle Δ^{++} only
$d\sigma/d\,COS(\theta)$ (nb/.1)
COS(θ_{π}+)

Fig. 15

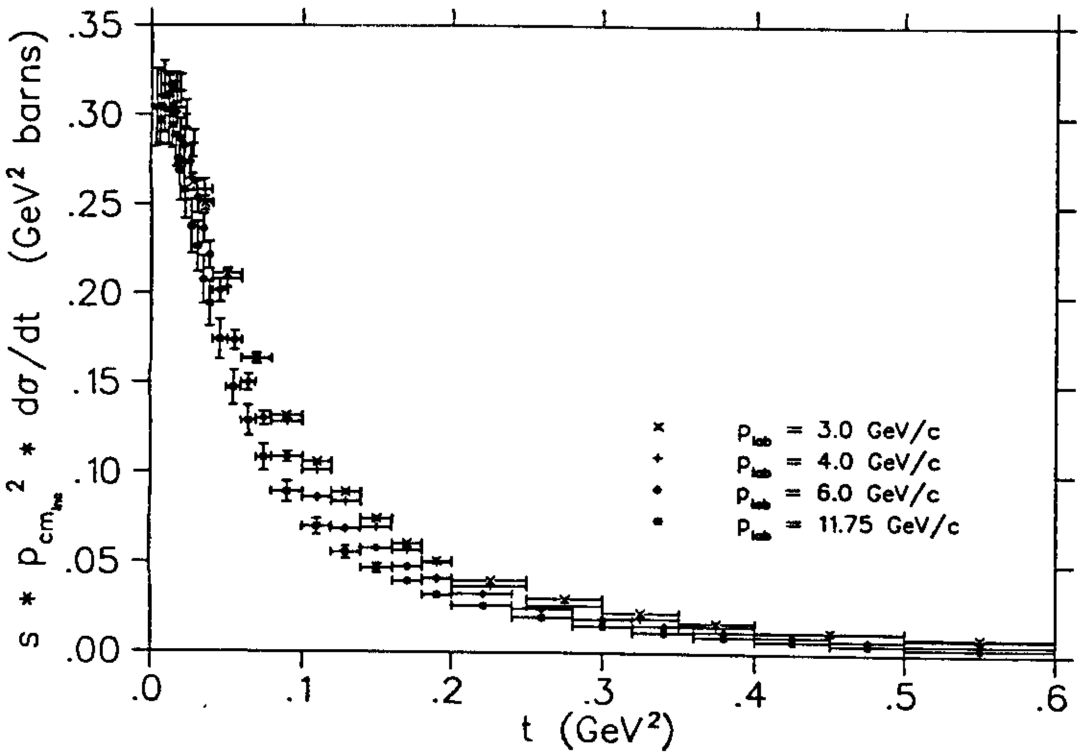

.35
.30
.25
.20
.15
.10
.05
.00
.0
.1
.2
.3
.4
.5
.6
t (GeV²)
s * p_cm_lab ² * dσ/dt (GeV² barns)
P_lab = 3.0 GeV/c
P_lab = 4.0 GeV/c
P_lab = 6.0 GeV/c
P_lab = 11.75 GeV/c

Fig. 16